Condition Variables

- multithreaded programs need more than just locks
- locks support mutual exclusion
- *condition variables* support waiting for a condition to become true
  - e.g. for a child thread to end (join)
  - e.g. producer/consumer (bounded buffer)
  - e.g. covering conditions

The Need For Condition Variables

- as we've seen with locks, spinning for any length of time is inefficient

```
volatile int done = 0;

void *child(void *arg) {
    printf("child\n");
    done = 1;
    return NULL;
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // child
    while (done == 0)
        ; // spin
    printf("parent: end\n");
    return 0;
}
```


Condition Variables – pthreads API

`#include <pthread.h>`

- a condition variable is just a queue for waiting threads
  - declaration, initialization, and cleanup

```
int pthread_cond_init(pthread_cond_t *cond,
    const pthread_condattr_t *attr);
int pthread_cond_destroy(pthread_cond_t *cond);
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;
```

    - `PTHREAD_COND_INITIALIZER` initializes with default values
  - put current thread to sleep (*wait*)

```
int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);
int pthread_cond_timedwait(pthread_cond_t *cond,
    pthread_mutex_t *mutex, const struct timespec *abstime);
```

    - `wait` requires first holding a lock (*`mutex`*)
  - wake up one (*signal*) or all *(broadcast)* waiting threads

```
int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_broadcast(pthread_cond_t *cond);
```


Implementing Join

Pthread operations are the wrapper versions

```
int done  = 0;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t c  = PTHREAD_COND_INITIALIZER;

void thr_exit() {
    Pthread_mutex_lock(&m);
    done = 1;
    Pthread_cond_signal(&c);
    Pthread_mutex_unlock(&m);
}

void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}

void thr_join() {
    Pthread_mutex_lock(&m);
    while (done == 0)
        Pthread_cond_wait(&c, &m);
    Pthread_mutex_unlock(&m);
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

have a state variable, not just `wait` and `signal`

it is good practice to hold the lock when calling signal, even though `signal` doesn't explicitly require it like `wait` does

lock must be held when wait is called – `wait` atomically releases the lock and puts the calling thread to sleep, then re-acquires the lock before returning when thread is awakened

loop instead of `if`

Incorrect

Pthread operations are the wrapper versions

```
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t c  = PTHREAD_COND_INITIALIZER;

void thr_exit() {
    Pthread_mutex_lock(&m);
    Pthread_cond_signal(&c);
    Pthread_mutex_unlock(&m);
}

void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}

void thr_join() {
    Pthread_mutex_lock(&m);
    Pthread_cond_wait(&c, &m);
    Pthread_mutex_unlock(&m);
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

no state variable

it is possible for the child to run immediately, before the parent calls `thr_join` and `wait`

if the child calls `signal` before the parent calls `wait`, the signal is lost and the parent is left waiting forever

if the child calls `signal` before the parent calls `wait`, the parent knows because done is 1 and thus doesn't wait

```
void thr_exit() {
    Pthread_mutex_lock(&m);
    done = 1;
    Pthread_cond_signal(&c);
    Pthread_mutex_unlock(&m);
}
```

```
void thr_join() {
    Pthread_mutex_lock(&m);
    while (done == 0)
        Pthread_cond_wait(&c, &m);
    Pthread_mutex_unlock(&m);
}
```


Incorrect

Pthread operations are the wrapper versions

```
int done  = 0;
pthread_cond_t c  = PTHREAD_COND_INITIALIZER;

void thr_exit() {
    done = 1;
    Pthread_cond_signal(&c);
}

void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}

void thr_join() {
    if (done == 0)
        Pthread_cond_wait(&c);
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

no lock

non-atomic test and act – if the child runs between the parent checking `done` and waiting, the child can call `signal` before the parent calls `wait`

Producer/Consumer (Bounded Buffer)

- one or more *producer* threads add to a buffer
- one or more *consumer* threads remove from the buffer

- e.g. multithreaded web server
  - requests come in from multiple clients
  - multiple threads on the server satisfy requests
- e.g. Unix pipes
  - output comes from one process and is consumed as input by another

- the buffer is a shared resource, so race conditions must be avoided

The Idea of Producer/Consumer

```
void *producer(void *arg) {
    int i;
    int loops = (int) arg;
    for (i = 0; i < loops; i++) {
        put(i);
    }
}

void *consumer(void *arg) {
    while (1) {
        int tmp = get();
        printf("%d\n", tmp);
    }
}
```

producer adds to the buffer

consumer removes from the buffer

```
int buffer;
int count = 0; // initially, empty

void put(int value) {
    assert(count == 0);
    count = 1;
    buffer = value;
}

int get() {
    assert(count == 1);
    count = 0;
    return buffer;
}
```

buffer holds (only) a single value (for now)

can only add to the buffer when it is empty (`assert` verifies that assumption – will crash if violated)

can only remove from the buffer when it has something in it (`assert` verifies that assumption – will crash if violated)

First Try

```
int buffer;
int count = 0; // initially, empty

void put(int value) {
    assert(count == 0);
    count = 1;
    buffer = value;
}

int get() {
    assert(count == 1);
    count = 0;
    return buffer;
}
```

```
void *producer(void *arg) {
    int i;
    int loops = (int) arg;
    for (i = 0; i < loops; i++) {
        put(i);
    }
}

void *consumer(void *arg) {
    while (1) {
        int tmp = get();
        printf("%d\n", tmp);
    }
}
```

- does this work?
  - no, unless the `put` and `get` calls are interleaved exactly right – two `puts` in a row or two `gets` in a row will result in a violated assertion
  - also race conditions within `put` and `get` themselves

Second Try

add a condition variable to wait for expected buffer status

```
int buffer;
int count = 0; // initially, empty

void put(int value) {
    assert(count == 0);
    count = 1;
    buffer = value;
}

int get() {
    assert(count == 1);
    count = 0;
    return buffer;
}
```

```
int loops; // must initialize somewhere...
cond_t  cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        if (count == 1)                        // p2
            Pthread_cond_wait(&cond, &mutex);  // p3
        put(i);                                // p4
        Pthread_cond_signal(&cond);            // p5
        Pthread_mutex_unlock(&mutex);          // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // c1
        if (count == 0)                        // c2
            Pthread_cond_wait(&cond, &mutex);  // c3
        int tmp = get();                       // c4
        Pthread_cond_signal(&cond);            // c5
        Pthread_mutex_unlock(&mutex);          // c6
        printf("%d\n", tmp);
    }
}
```

- does this work?
  - with a single producer and a single consumer
    - lock means can't be signaled between checking count and waiting
    - once waiting, only the other thread can wake
    - only one thread can be waiting at a time
  - with more than one producer and/or consumer
    - assumption is that when `wait` returns, the buffer is ready for us

Second Try

two consumers, one producer

T_{c1}	State	T_{c2}	State	T_p	State	Count	*Comment*
c1	Run		Ready		Ready	0	
c2	Run		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep		Ready	p1	Run	0	
	Sleep		Ready	p2	Run	0	
	Sleep		Ready	p4	Run	1	Buffer now full
	Ready		Ready	p5	Run	1	T_{c1} awoken
	Ready		Ready	p6	Run	1	
	Ready		Ready	p1	Run	1	
	Ready		Ready	p2	Run	1	
	Ready		Ready	p3	Sleep	1	Buffer full; sleep
	Ready	c1	Run		Sleep	1	T_{c2} sneaks in ...
	Ready	c2	Run		Sleep	1	
	Ready	c4	Run		Sleep	0	... and grabs data
	Ready	c5	Run		Ready	0	T_p awoken
	Ready	c6	Run		Ready	0	
c4	Run		Ready		Ready	0	Oh oh! No data

```
int loops; // must initialize somewhere...
cond_t  cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        if (count == 1)                        // p2
            Pthread_cond_wait(&cond, &mutex);  // p3
        put(i);                                // p4
        Pthread_cond_signal(&cond);            // p5
        Pthread_mutex_unlock(&mutex);          // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // c1
        if (count == 0)                        // c2
            Pthread_cond_wait(&cond, &mutex);  // c3
        int tmp = get();                       // c4
        Pthread_cond_signal(&cond);            // c5
        Pthread_mutex_unlock(&mutex);          // c6
        printf("%d\n", tmp);
    }
```


Mesa vs Hoare Semantics

Mesa semantics – (how pretty much every system works)

- signal only wakes a thread
  - being signaled reflects a certain state of the world at that moment but there are no guarantees that state still holds when the thread finally runs

Hoare semantics – (nice but harder to implement)

- signal wakes a thread *and* guarantees that it runs immediately

Third Try

`while` instead of `if`

```
int loops; // must initialize somewhere...
cond_t  cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        while (count == 1)                     // p2
            Pthread_cond_wait(&cond, &mutex);  // p3
        put(i);                                // p4
        Pthread_cond_signal(&cond);            // p5
        Pthread_mutex_unlock(&mutex);          // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // c1
        while (count == 0)                     // c2
            Pthread_cond_wait(&cond, &mutex);  // c3
        int tmp = get();                       // c4
        Pthread_cond_signal(&cond);            // c5
        Pthread_mutex_unlock(&mutex);          // c6
        printf("%d\n", tmp);
    }
}
```

```
int buffer;
int count = 0; // initially, empty

void put(int value) {
    assert(count == 0);
    count = 1;
    buffer = value;
}

int get() {
    assert(count == 1);
    count = 0;
    return buffer;
}
```

- does this work?
  - the problem of a buffer status change between waking and access is fixed
  - but a single condition variable means that both producers and consumers wait, and thus a thread can be woken by another thread of the same kind rather than the opposite...and if it can't do its job, it goes back to sleep and no one else gets signaled

Third Try

two consumers, one producer

T_{c1}	State	T_{c2}	State	T_p	State	Count	*Comment*
c1	Run		Ready		Ready	0	
c2	Run		Ready		Ready	0	
c3	Sleep		Ready		Ready	0	Nothing to get
	Sleep	c1	Run		Ready	0	
	Sleep	c2	Run		Ready	0	
	Sleep	c3	Sleep		Ready	0	Nothing to get
	Sleep		Sleep	p1	Run	0	
	Sleep		Sleep	p2	Run	0	
	Sleep		Sleep	p4	Run	1	Buffer now full
	Ready		Sleep	p5	Run	1	T_{c1} awoken
	Ready		Sleep	p6	Run	1	
	Ready		Sleep	p1	Run	1	
	Ready		Sleep	p2	Run	1	
	Ready		Sleep	p3	Sleep	1	Must sleep (full)
c2	Run		Sleep		Sleep	1	Recheck condition
c4	Run		Sleep		Sleep	0	T_{c1} grabs data
c5	Run		Ready		Sleep	0	Oops! Woke T_{c2}
c6	Run		Ready		Sleep	0	
c1	Run		Ready		Sleep	0	
c2	Run		Ready		Sleep	0	
c3	Sleep		Ready		Sleep	0	Nothing to get
	Sleep	c2	Run		Sleep	0	
	Sleep	c3	Sleep		Sleep	0	Everyone asleep...

```
int loops; // must initialize somewhere...
cond_t  cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        while (count == 1)                     // p2
            Pthread_cond_wait(&cond, &mutex);  // p3
        put(i);                                // p4
        Pthread_cond_signal(&cond);            // p5
        Pthread_mutex_unlock(&mutex);          // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // c1
        while (count == 0)                     // c2
            Pthread_cond_wait(&cond, &mutex);  // c3
        int tmp = get();                       // c4
        Pthread_cond_signal(&cond);            // c5
        Pthread_mutex_unlock(&mutex);          // c6
        printf("%d\n", tmp);
    }
}
```


Fourth Try

separate condition variables for empty buffer and full buffer

```
int loops; // must initialize somewhere...
cond_t  empty, fill;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 1)
            Pthread_cond_wait(&empty, &mutex);
        put(i);
        Pthread_cond_signal(&fill);
        Pthread_mutex_unlock(&mutex);
    }
}
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 0)
            Pthread_cond_wait(&fill, &mutex);
        int tmp = get();
        Pthread_cond_signal(&empty);
        Pthread_mutex_unlock(&mutex);
        printf("%d\n", tmp);
    }
}
```

```
int buffer;
int count = 0; // initially, empty

void put(int value) {
    assert(count == 0);
    count = 1;
    buffer = value;
}

int get() {
    assert(count == 1);
    count = 0;
    return buffer;
}
```

- does this work?
  - yes!

Full Producer/Consumer Solution

```
int buffer[MAX];
int fill_ptr = 0;
int use_ptr  = 0;
int count    = 0;

void put(int value) {
    buffer[fill_ptr] = value;
    fill_ptr = (fill_ptr + 1) % MAX;
    count++;
}
int get() {
    int tmp = buffer[use_ptr];
    use_ptr = (use_ptr + 1) % MAX;
    count--;
    return tmp;
}
```

add more slots to the buffer

use a circular array implementation of a queue – `use_ptr` at the head, `fill_ptr` at the tail – to avoid shifting and achieve O(1) operations

not thread safe – why not, and why is this not a problem?

```
int loops; // must initialize somewhere...
cond_t empty, fill;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == MAX)
            Pthread_cond_wait(&empty, &mutex);
        put(i);
        Pthread_cond_signal(&fill);
        Pthread_mutex_unlock(&mutex);
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 0)
            Pthread_cond_wait(&fill, &mutex);
        int tmp = get();
        Pthread_cond_signal(&empty);
        Pthread_mutex_unlock(&mutex);
        printf("%d\n", tmp);
    }
}
```